STUDY OF THE INFLUENCE OF TEMPERATURE ON THE MEASUREMENT ACCURACY OF TRANSIT-TIME ULTRASONIC FLOWMETERS

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ABSTRACT:

Flow measurement has a profound impact on industrial production and people's daily life. In order to improve the accuracy of ultrasonic flowmeter measurement, it is very important to study the influence of ultrasonic flowmeter measurement accuracy factors. Qualitative and quantitative analysis of the causes of measurement error caused by temperature is made, and a mathematical model is established. The experimental data is processed and analyzed, and the temperature compensation coefficient of flow measurement is obtained. When the pump speed is certain (respectively, 30n/s, 40n/s, 50n/s, 60n/s, 70n/s, 80n/s, 90n/s, 100n/s), the flow rate is measured at different temperatures (respectively, at 19℃, 24℃, 27℃, 30℃, 33℃, 35℃, 37℃, 39℃). The experimental results show that the flow measurement results by temperature compensation are helpful in improving the measurement accuracy of the ultrasonic flowmeter. This study has certain application value, which can provide theoretical support for the design of high-precision ultrasonic flowmeters and design guidance.

Keywords: transit-time ultrasonic flowmeter, the flow measurement, accuracy of measurement, the temperature influence.

1 INTRODUCTION

Measurement is essential to the development of science and technology, economy and society[1]. Flow measurement, as an important part of measurement science, has a profound impact on industrial production and people's daily life[2].With the increasingly severe energy problem, the requirement for flow meters is increasing, especially in the transmission and measurement of water, oil and gas, etc. The accuracy of measurement is a matter of great concern[3]. Ultrasonic flowmeters are widely used due to its advantages such as simple operation, good adaptability to pipe diameter, does not make any contact with fluid and ease of digital management[4]. In recent years, the rapid development of electronic technology and its related theory has contributed to the further improvement of the accuracy of ultrasonic flow measurement, which promotes the development of ultrasonic flowmeters for high performance and intelligent direction[5]. Today, more than 50 of the world's large ultrasonic flowmeter manufacturers are concentrated in Europe, USA, Japan, etc[6]. In China, the research into ultrasonic flowmeters started relatively late, and the advanced technology of ultrasonic flowmeters cannot reach an international level, which makes the accuracy of the ultrasonic flowmeter quite low[7]. To this end, independent research and development of a high precision ultrasonic flowmeter is extremely important.

Transit-time ultrasonic flowmeters have been favored by more and more scholars because of their outstanding advantages. The main performance indexes are measurement accuracy and repeatability[8]. The improvement of these indicators mainly depends on the measurement of ultrasonic flight time, as fluid distribution, performance and installation precision of the transducer, and the flight time of measurement accuracy all play a decisive role in measurement accuracy[9].There are many factors that influence the measurement accuracy of ultrasonic flowmeters, with temperature as an important influence factor getting more and more attention. Solutions to error caused by temperature factors are also being studied increasingly[10]. Modeling the influence of temperature variation on ultrasonic flowmeters and the design of high precision flow parameter measurement systems based on it, has a very important role and significance in improving the accuracy of the ultrasonic flowmeter.

2 THE PRESENT RESEARCH SITUATION

At present, the development directions of transit-time ultrasonic flowmeters are to improve the timing accuracy and to reduce the impact of temperature on the measurement accuracy[11]. Many scholars at home and abroad have done a lot of research to improve the timing accuracy of ultrasonic flowmeters. For example, based on the traditional phase-locked loop timing theory and the edge detection technology, a new time-measuring method was proposed by Zheng Peng, Wang Yong, et al[12]. The generalized cross correlation delay method based on BP neural network filtering was proposed by Gao Zheng Zhong, which can be used to improve the timing accuracy in complex conditions[13]. Liling Ma et al. of Beijing Institute of Technology proposed an improved spline-based algorithm to reduce computational complexity while maintaining accuracy[14]. The effect of the separation distance between the transducers on the output signal of the flowmeter was studied by Dharshanie V. Mahadeva et al, to minimize errors by setting the transducers at the correct separation distance[15]. For direct determination of the acoustical calibration factor of ultrasonic flowmeters, a new method was proposed by O. Keitmann-Curdes and B. Funck[16].

Transit-time ultrasonic flowmeters are sensitive to temperature and their measurement accuracy is susceptible to temperature. The mentioned research did not focus on the influence of temperature on the ultrasonic flowmeter. This paper focuses on the influence of temperature on the measurement accuracy of ultrasonic flowmeters. Finally, the temperature compensation coefficient of flow measurement is obtained, and the measurement accuracy of ultrasonic flowmeters is improved.

3 MEASUREMENT ERROR MODEL OF ULTRASONIC FLOWMETER CAUSED BY TEMPERATURE

3.1 EFFECT OF TEMPERATURE ON ULTRASONIC VELOCITY IN PIPE WALL

Ultrasonic velocity is closely related to the elastic modulus and density when an ultrasonic wave propagates in the pipe wall[17]. Since the transverse wave can only be propagated in the solid, the transmission of the ultrasonic flowmeter transducers must be in the form of a longitudinal wave. In an infinite solid medium, the ultrasonic longitudinal wave velocity can be expressed as[17]:

$$C_1 = \sqrt{\frac{E}{\rho} \cdot \frac{1-\upsilon}{(1+\upsilon)(1-2\upsilon)}} = \sqrt{\frac{K+4/3G}{\rho}} \tag{1}$$

Where E is young's modulus, ρ is medium density; υ is Poisson's ratio; K is the bulk modulus; G is shear modulus. In the field of oil and gas storage and transportation, oil and gas pipelines often use metal materials. At different temperatures, the density of the metal changes. Taking into account the volume expansion of the metal at each temperature, the relationship between the change of metal density and the temperature can be expressed as[17]:

$$\rho_T = \frac{m}{V_0(1+3\alpha\Delta T)} \tag{2}$$

Where m is a metal quality; V_0 is the volume of metal for 293K ; α is the thermal expansion coefficient of metal; and ΔT is the amount of temperature change. The velocity formula of ultrasonic waves in metals at different temperatures can be derived from Eq. (1) and Eq. (2):

$$C_1 = \sqrt{\frac{V_0}{m}\left(K + \frac{4}{3}G\right)(1 + 3\alpha\Delta T)} \tag{3}$$

3.2 EFFECT OF TEMPERATURE ON ULTRASONIC VELOCITY IN LIQUID

In order to establish the velocity relation of ultrasonic waves in liquid, it is assumed that the liquid is the ideal liquid, uniform and continuous, in thermodynamic equilibrium in stationary state, and the only motion is caused by the sound wave itself, while the amplitude of the motion is small enough that many nonlinear effects can be ignored[18].

（1）WAVE EQUATION OF ULTRASONIC WAVE IN LIQUID

Water, hydrochloric acid, hydrogen peroxide and other liquids are elastic media that have quality and flexibility[18]. The elasticity causes the fluid to resist compression and have a tendency to return to its original state, but the inertia of mass produces too much movement. The two conditions of the wave are provided[18].

$$K_T = -\frac{1}{V}\left(\frac{\partial V}{\partial P}\right)^T = \frac{1}{\rho}\left(\frac{\partial \rho}{dP}\right)^T \tag{4}$$

$$U = \frac{1}{V}\left(\frac{\partial V}{\partial T}\right)^P = \frac{1}{\rho}\left(\frac{\partial \rho}{dT}\right)^P \tag{5}$$

Where K_T is the isothermal compression rate of fluid ; U for the thermal expansion coefficient of the fluid; ρ is the static density of the fluid; P is the static pressure of the fluid; V is the volume of the fluid[12]. The wave equation of the sound wave is:

$$\frac{\partial^2}{\partial x^2} = \frac{1}{C_2^2}\frac{\partial^2}{\partial t^2} \tag{6}$$

Where $C_2^2 = 1/K\rho$, C is the propagation velocity of the ultrasonic wave in the liquid and is related to the density of the liquid ρ and the compression coefficient K[18].

（2）THE RELATIONSHIP BETWEEN ADIABATIC COMPRESSION COEFFICIENT AND TEMPERATURE

The compression coefficient changes little with the temperature, and changes much with the pressure. The compression coefficient can be expressed as[19]:

$$K = K_0(1 + X\Delta t) \tag{7}$$

When the temperature is T_0, the K_0 is the compression coefficient; X is the coefficient of variation of the compression coefficient with temperature; and Δt is the change in temperature.

（3）THE RELATIONSHIP BETWEEN DENSITY AND TEMPERATURE OF LIQUID

The change in the density of the liquid when the temperature changes is a non-negligible quantity relative to the change of the compression system when the temperature changes. The density changes with temperature are not linear[20]. They can be replaced by a quadratic curve:

$$\rho = \rho_0(1 + \beta_1\Delta t + \beta_2\Delta t^2) \tag{8}$$

Where ρ_0 is the density of liquid when the temperature is T_0,β_1,$\beta_2$are one and two term coefficients, respectively.

（4）SYNTHETIC EXPRESSION OF ULTRASONIC VELOCITY OF LIQUID

Using comprehensive Eq. (11) (12) and (13), we know:

$$C_2^2 = \frac{C_0^2}{(1+X\Delta t)(1+\beta_1\Delta t+\beta_2\Delta t^2)} \approx \frac{C_0^2}{[1+(X+\beta_1)\Delta t+\beta_2\Delta t^2]} \tag{9}$$

3.3 THE INFLUENCE OF TEMPERATURE ON THE SOUND PATH

The pipe wall is usually a metallic material. The temperature changes make the metal expand linearly, leading to the change of the sound path. When the temperature change is Δt[21], the expression of the sound path is[21]:

$$L = L_0(1 + U\Delta t) \tag{10}$$

Where $L_0$is the sound path at T_0℃; U is the expansion coefficient of the metal wire.

3.4 EFFECT OF TEMPERATURE ON VOLUME AND MASS FLOW RATE

The energy required for the fluid to pass through a heat transfer is proportional to the product of the volume of fluid and pressure drop. The cross-sectional area of the pipeline is constant, volume flow is proportional to the velocity, and the heat exchange energy is conserved:

$$(\frac{\mu_t}{\rho_t V_t d})^{0.25} V_t^3 = (\frac{\mu_0}{\rho_0 V_0 d})^{0.25} V_0^3 \tag{11}$$

Where μ and ρ are the fluid dynamic viscosity and density respectively, d is the inner diameter of the pipe for the pipe side, and the equivalent diameter for the shell side. The subscripts t and 0 mean the condition oft ℃ and 0 ℃. The volume flow rate at different temperatures is:

$$\frac{V_0}{V_t} = (\frac{\mu_t \rho_0}{\mu_0 \rho_t})^{0.096} \tag{12}$$

The mass flow ratio is:

$$\frac{m_0}{m_t} = \frac{V_0\rho_0}{V_t\rho_t} = (\frac{\mu_0}{\mu_t})^{0.091}(\frac{\rho_0}{\rho_t})^{1.091} \quad (13)$$

For fluids, μ and ρ all decrease with an increase in temperature and the volume of fluid flow and mass flow rate increases with an increase in temperature[22]. When fluid viscosity is low or fluid viscosity does not change with the temperature, the flow rate change with the temperature is small[22].

3.5 AN INTEGRATED MODEL OF TEMPERATURE INFLUENCE ON THE MEASUREMENT ACCURACY OF ULTRASONIC FLOWMETERS

According to the principle of time difference of ultrasonic known: current time is:

$$t_1 = 2\frac{d_0(1+U\Delta t)}{\sin\theta\cdot C_1} + \frac{D}{\sin\theta\cdot(C_2+V\,co\;\;\theta)}, \quad (14)$$

Counter current time

$$t_2 = 2\frac{d_0(1+U\Delta t)}{\sin\theta\cdot C_1} + \frac{D}{\sin\theta\cdot(C_2-V\,c\;\;\;\theta)}, \quad (15)$$

So the time difference is:

$$\Delta T = t_2 - t_1 = \frac{2DV\,co}{C_2^2 - V^2\cos^2\theta} = \frac{2LV\,co}{C_2^2 - V^2\cos^2\theta} \quad (16)$$

The instantaneous velocity in the pipe $V(t) = \frac{C_2^2\cdot\Delta T}{2L\cos\theta}$; and the transverse section area of the pipe walls $= \frac{\pi}{4}(D - d_0(1 + U\Delta t))^2$; In $[t_2, t_1]$ period, total flow F is:

$$F = \int_{t_1}^{t_2} f(t)dt = \int_{t_1}^{t_2} V(t)\cdot Sdt \quad (17)$$

4 SYSTEM DESIGN BASED ON FPGA

The FPGA chip is used to design high frequency clock circuits with dozens or even hundreds of megabytes[23]. Altera's Cyclone II series chips were chosen with a working frequency of up to 400 MHZ - enough to meet the needs of the design[23]. The software development platform was the Quartus Ⅱ.The overall block diagram of the system is shown in Figure 1:

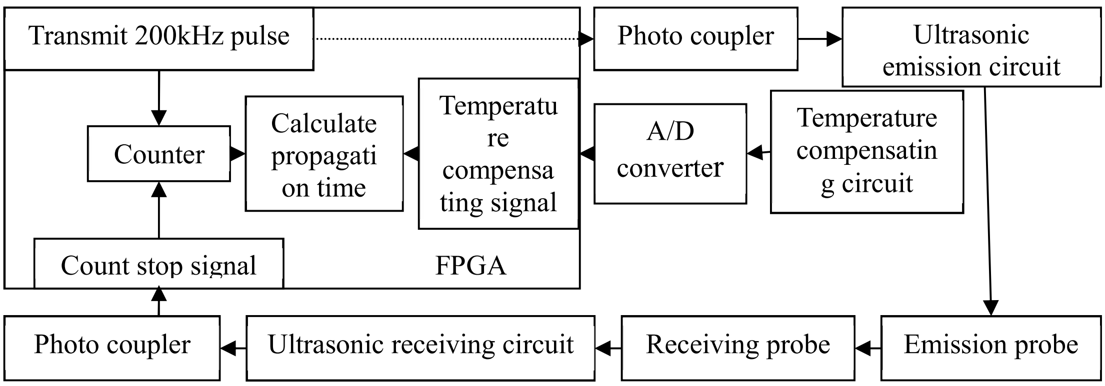

Fig.1. System schematic circuit diagram

The FPGA chip outputs the pulse of 200kHz ， which is coupled to the ultrasonic transmitting circuit through the photoelectric coupler, and the signal is sent through the transmitting probe. When the feedback pulse signal is detected by the receiving probe, it is processed by the receiving circuit, and then the signal is transmitted back to FPGA through the photoelectric coupler.

When the signal is sent, the FPGA internal counter starts counting. It stops counting when the FPGA receives the signal. The temperature compensation signal is detected by the temperature compensation circuit. Firstly, the temperature of the fluid is detected through the temperature compensation circuit and AD conversion. Secondly, the FPGA receives the temperature compensation signal and corrects the time deviation. Finally, the counter calculates the propagation time of corrected ultrasound.

The system program used is the VHDL language program. Using modular programming ideas, the preparation of the data acquisition program interrupts the service routines and main program. The actual diagram of the whole experimental setup is shown in Fig 2.

Fig.2 Actual diagram of the whole experimental setup

5 TEMPERATURE EFFECT ULTRASONIC FLOWMETER MEASUREMENT ACCURACY EXPERIMENTAL MEASUREMENTS

5.1 PRINCIPLE

In practical engineering applications, the internal temperature of the pipeline is not easy to measure. In the present study, a standard test specimen is adhered to the surface of the pipe wall. According to the properties of heat conduction, the temperature of the standard test specimen is the same as that of the pipe[24]. The schematic diagram of the experimental apparatus is shown in figure 3.

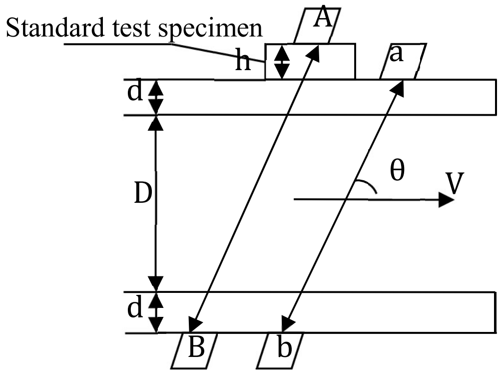

Fig.3. Schematic diagram of experimental set-up

The experimental device diagram is shown in Figure 2, in which the AB probe is installed on the standard test specimen. The A and a probes are the launch probes and the B and b probes are the receiver probes. The time that the B probe receives the ultrasonic signal will be delayed by ΔT from the b probe[25]. The ΔT can be expressed as:

$$\Delta T = \frac{h_0(1+\alpha\Delta t)}{C_\alpha \sin\theta} = \frac{h_0(1+\alpha\Delta t)}{\sqrt{\frac{V_0}{m}\left(K+\frac{4}{3}G\right)(1+3\alpha\Delta t)}\sin\theta} \tag{18}$$

And thus we can get a more accurate temperature Δt:

$$\Delta t = \frac{\left(3X-2\alpha h_0^2\right)+\sqrt{4\alpha^2 h_0^2\left(h_0^2-X\right)}}{2\alpha^2 h_0^2} \tag{19}$$

Where $X = \frac{V_0}{m}\left(K+\frac{4}{3}G\right)\sin^2\theta\,\Delta T^2$; $h_0$is the height of the standard test specimen at 0℃; α is the coefficient of linear expansion of the standard test specimen; θ is the angle between the connecting line of the transducer and the radial direction of the pipe; V_0 is the volume of the standard test specimen at 0℃; M is the quality of the standard test specimen; K is the bulk modulus of the standard test specimen; and G is the shear modulus of the standard test specimen[26].

5.2 DATA ANALYSIS

The relationship between temperature and flow in the laboratory is shown in Table 1:

Tab.1. Experimental data of temperature and flow

temperature°C flow m³/ Pump speed n/s	19	24	27	30	33	35	37	39
30	1.36	1.36	1.35	1.35	1.35	1.34	1.34	1.34
40	1.95	1.93	1.93	1.92	1.91	1.90	1.87	1.86
50	2.56	2.54	2.53	2.51	2.49	2.48	2.46	2.46
60	3.17	3.16	3.14	3.12	3.11	3.08	3.06	3.05
70	3.66	3.64	3.61	3.59	3.55	3.52	3.48	3.47
80	4.05	4.00	3.97	3.92	3.89	3.84	3.81	3.77
90	4.44	4.39	4.36	4.33	4.27	4.25	4.19	4.16
100	4.74	4.71	4.67	4.62	4.58	4.55	4.49	4.45

The fitting results of the experimental data curve are shown in figure 4.

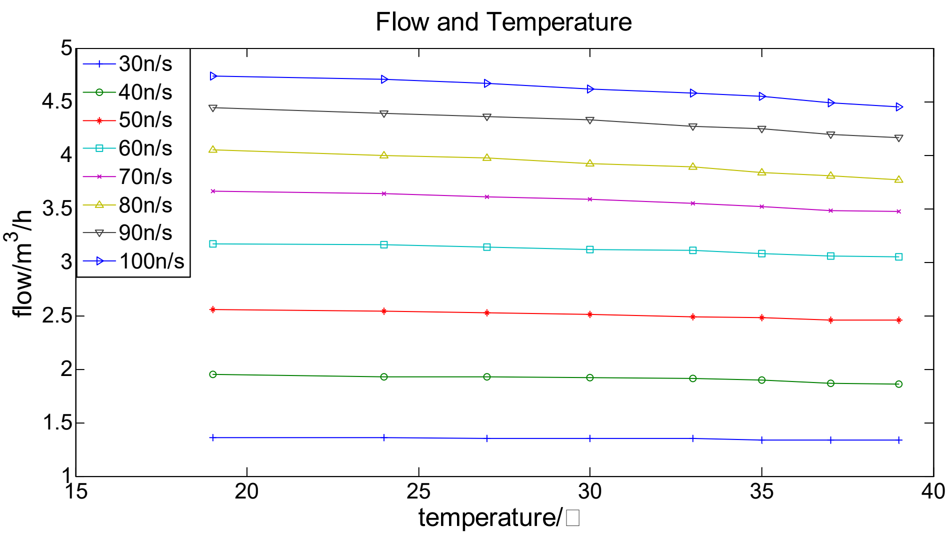

Fig.4. Experimental data curve fitting results

From Table 1, it is shown that when the temperature is higher, the greater the actual measurement value and the ideal value. The temperature compensation of the ultrasonic flowmeter can improve the measurement accuracy of the ultrasonic flowmeter. According to the pump speed, pipe diameter and accurate temperature values on Δt can be oppositely deduced using the temperature compensation coefficient $\Delta\varphi$, which is a piecewise function. Concrete is represented as:

$$\Delta\varphi = \alpha + \beta\Delta t + \gamma\Delta t^2 \quad (22)$$

According to different temperature, we use MATLAB to calculate the α,β,γ coefficients as shown in Table 2.

Tab.2. Correction coefficients of flow rate under different temperature

℃	17-22	23-25	26-28	29-31	32-34	35-36	37-38	39-40
α	0.027630	0.126932	-0.008018	0.168992	0.195574	0.182526	0.186410	0.341223
β	0.000333	-0.007666	0.001031	-0.006227	-0.009393	-0.014732	-0.008614	-0.013548
γ	0.000014	0.000204	0.000075	0.000216	0.000336	0.000554	0.000389	0.000485

The correction values of the flow rate at different temperatures at different pump speeds are shown in Table 3.

Tab.3. Flux correction values at different temperatures in theory

temperature℃ flow m^3/ Pump speed n/s	19	24	27	30	33	35	37	39
30	0.039	0.044	0.047	0.050	0.054	0.056	0.059	0.062
40	0.055	0.061	0.069	0.081	0.096	0.109	0.123	0.138
50	0.039	0.060	0.075	0.090	0.108	0.120	0.133	0.146
60	0.129	0.144	0.158	0.177	0.199	0.216	0.234	0.255
70	0.138	0.164	0.187	0.216	0.252	0.278	0.308	0.340
80	0.103	0.148	0.189	0.239	0.300	0.346	0.396	0.451
90	0.163	0.204	0.237	0.278	0.326	0.361	0.400	0.442
100	0.259	0.295	0.329	0.371	0.422	0.461	0.504	0.551

The schematic diagram is shown in figure 5.

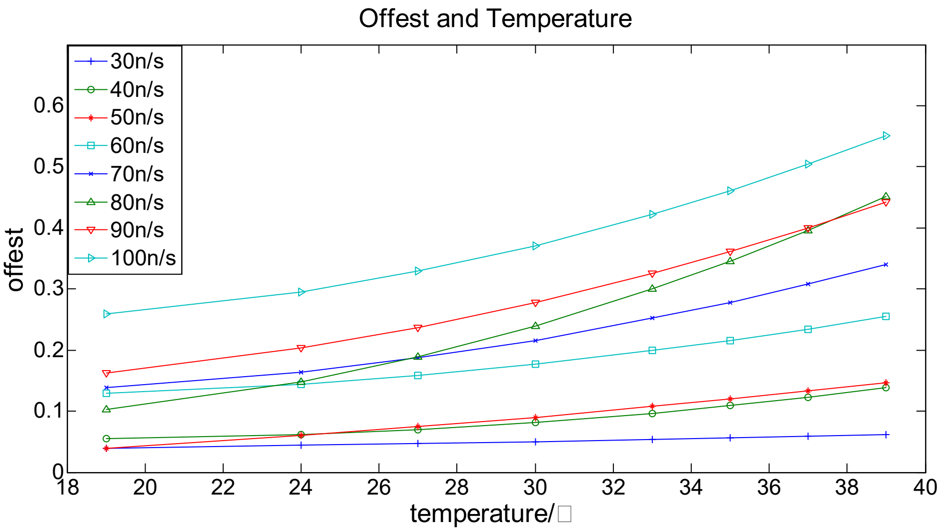

Fig.5. Theoretically different pump speed temperature compensation

Theoretically, the ultrasonic flow values with temperature compensation are shown in Table 4.

Tab.4. Theoretical values of ultrasonic flowmeters with temperature compensation

temperature°C flow m³/ Pump speed n/s	19	24	27	30	33	35	37	39
30	1.401	1.405	1.404	1.406	1.408	1.405	1.405	1.405
40	2.009	1.998	2.001	2.009	2.011	2.012	1.994	1.998
50	2.602	2.602	2.606	2.600	2.604	2.604	2.602	2.609
60	3.303	3.306	3.304	3.305	3.314	3.302	3.303	3.308
70	3.803	3.809	3.803	3.809	3.803	3.803	3.795	3.816
80	4.157	4.149	4.159	4.162	4.198	4.191	4.209	4.222
90	4.605	4.600	4.605	4.617	4.596	4.613	4.592	4.607
100	4.999	5.006	4.992	4.997	5.006	5.013	4.994	5.007

The accurate flow rates at different pump speeds are shown in Table 5.

Tab.5. Accurate flow rates at different pump speeds

Pump speed n/s	30	40	50	60	70	80	90	100
Flow m³/h	1.400	2.000	2.600	3.300	3.800	4.200	4.600	5.000

According to the experimental results, the actual flow values should be corrected as shown in Table 6.

Tab.6. The actual values of the flow that should be corrected in the test

temperature°C flow m³/ Pump speed n/s	19	24	27	30	33	35	37	39
30	0.038	0.039	0.043	0.044	0.046	0.051	0.054	0.057
40	0.046	0.063	0.068	0.072	0.085	0.097	0.129	0.140
50	0.037	0.058	0.069	0.090	0.104	0.116	0.131	0.137
60	0.126	0.138	0.154	0.172	0.185	0.214	0.231	0.247
70	0.135	0.155	0.184	0.207	0.249	0.275	0.313	0.324
80	0.146	0.199	0.230	0.277	0.302	0.355	0.387	0.429
90	0.158	0.204	0.232	0.261	0.330	0.348	0.408	0.435
100	0.260	0.289	0.328	0.374	0.416	0.448	0.510	0.544

After eliminating gross error, comparing Table 3 and Table 6 we find that the maximum error between the actual correction flow value and the theoretical correction value calculated by the formula is within 8.92% and error decreases with the increase in pump speed. The reason is that the liquid is modeled over the full pipe state in this formula, and there is no analysis of the liquid in the case of insufficient pipe or if mixed with a certain amount of air. And the lower the pump speed, the more the air goes into the pipe and the greater the error value. At pump speeds of 30n/s, 70n/s and 100n/s, the contrast diagram of uncorrected flow rates, corrected flow rates and the exact values is shown in Figure 6.

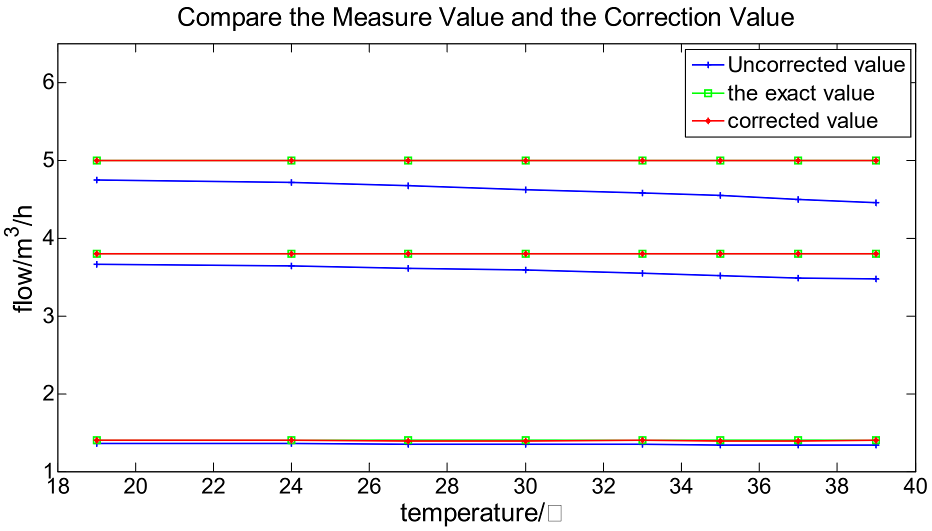

Fig.6. The measured values under different pump speeds compared with revised figures

6 CONCLUSIONS

Based on the influence of temperature change on the measurement precision of ultrasonic flowmeters, a hardware testing system has been designed that provides a more powerful guarantee for the precise measurement of ultrasonic flowmeters. The following conclusions are obtained:

(1) In view of the influence of temperature on the sound velocity of ultrasonic waves in solid and liquid and the change of the ultrasonic wave caused by the expansion coefficient of the pipe line, an influence error model is established.

(2) Based on the integrated influence error model, a design scheme for a high precision ultrasonic flowmeter test system is presented.

(3) Through a laboratory test, data on the relationship between temperature and flow is obtained. Through comparison with theoretical values, it is proven that the design has the advantages of high precision and temperature compensation, which can meet the demands of flow measurement.

ACKNOWLEDGEMENTS

This work is supported by scientific research starting project of SWPU (No 2014QHZ029), national natural science foundation of China (No 21204139), the State

Administration of National Security (No sichuan-009-2013AQ, No sichuang-0021-2014AQ), and the Sichuan Educational Committee (No 15ZB0060).

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